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TEMPERATURE COMPENSATION OF LAMINAR PROPORTIONAL AMPLIFIERS USI--ETC(U)

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A theoretical and experimental study has been conducted on the use of the linear resistor bypass to compensate the supply nozzle Reynolds number of the laminar proportional amplifier (LPA) for temperature changes. Both the theoretical and experimental results indicate that the linear resistor bypass is a limited method for temperature compensation for the present LPA design

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because the supply nozzle of the LPA has a large linear resistance component. Even without the supply nozzle linear component, the best that one can achieve is limited as indicated by the following equation:

$$Q_s = \frac{Q_T}{1 + \frac{K_s Q_s}{R_{b\ell}}} ,$$

where

Q_s = supply flow rate,
Q_T = total flow rate,
K_s = coefficient of the nonlinear component of the supply nozzle, and
$R_{b\ell}$ = linear component of the bypass resistor.

The ideal ratio $\eta = (N_{Rf} - N_{Ri})_c/(N_{Rf} - N_{Ri})_u$ (where N_R is the Reynolds number, and the subscripts f, i, c, and u correspond to final, initial, compensated, and uncompensated) approaches 0.4 and 0.32 as Q_s/Q_T approaches zero for $\mu_f = 1/2\ \mu_i$ and $\mu_f = 1/5\ \mu_i$, respectively, where μ is dynamic viscosity.

In general, for a given viscosity range, the ratio η decreases as Q_S/Q_T decreases. Even though it is desirable to limit the variation in the Reynolds number over the military temperature range, we have to increase the total power supply to the system. Therefore, it is necessary to compromise between the value of the ratio η and the total supply flow to the compensated system.

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1. INTRODUCTION

The purpose of this study is to extend the operating temperature range of the laminar proportional amplifier (LPA) (fig. 1) operating in hydraulic fluid by using a linear resistor bypass from the supply to the vent. This extension would allow the LPA to operate over a temperature range of 4.4 to 70 C. Within this temperature range, the kinematic viscosity of 5606 hydraulic oil changes from 40 to 7 centistoke, or about six times. This large change of viscosity presents a problem to the present LPA design because the LPA cannot operate satisfactorily over this temperature range because of variations in pressure gain, G_p, within the Reynolds number range. In order to maintain the pressure gain of the LPA within an acceptable level under these conditions, temperature compensation is needed. There are several ways to compensate the temperature effects; methods under consideration are linear resistor bypass, feedback, and power supply conditioning. This report deals only with the method of a linear resistor bypass. Test equipment limitations restricted the experimental temperature range to 15 to 55 C.

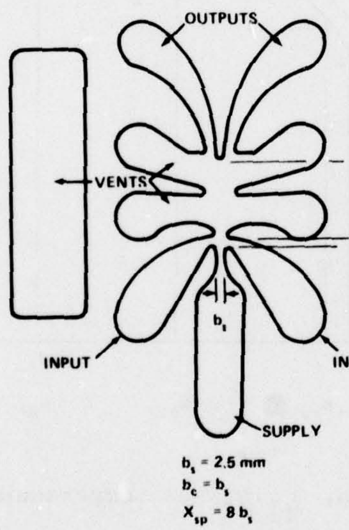

Figure 1. Schematic of laminar proportional amplifier.

2. THEORETICAL CONSIDERATIONS

The pressure gain of the LPA can be characterized by the Reynolds number $N_R = \bar{U}h/\nu$, based on average velocity, $\bar{U}$, channel height, h, and kinematic viscosity, ν. In general, G_p increases with N_R. At constant flow rate, the pressure gain increases as the hydraulic fluid temperature increases because N_R increases. Figure 2 illustrates the

problem. Assume that T_1 to T_4 is the desired temperature range. For this temperature range the pressure gain of a typical LPA varies from G_{p1} to G_{p4}, which is more than the desired gain variation of G_{p2} to G_{p3}. It is obvious that an acceptable solution to this problem is to have an LPA with a G_p versus N_R characteristic as shown by the dotted line in figure 2. At present, however, we do not have the desired LPA to meet the temperature requirement. In order to maintain the gain within G_{p2} to G_{p3} over the desired temperature range (T_1 to T_4), we have to temperature compensate the power supply so that the effective Reynolds number range is reduced to $\left(N_{R2} \text{ to } N_{R3}\right)$ from $\left(N_{R1} \text{ to } N_{R4}\right)$.

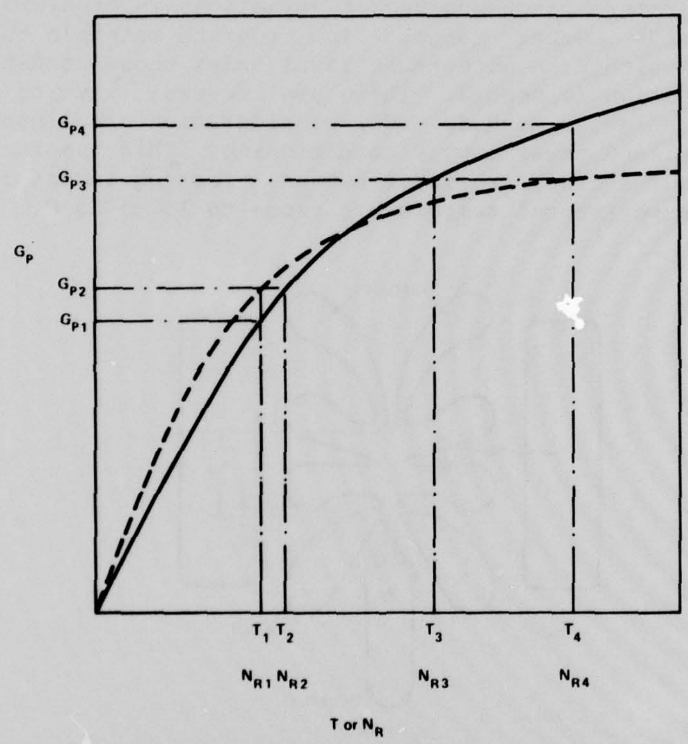

Figure 2. Pressure gain, G_p, versus temperature, T, and Reynolds number, N_R.

3. LINEAR RESISTOR BYPASS FOR HYDRAULIC OPERATION

In order to maintain the N_R through the LPA supply nozzle at a manageable range throughout the modified temperature range (4.4 to 70 C), we have to increase the supply flow rate, Q_s, as the fluid temperature decreases, and decrease the flow rate as the fluid temperature increases. Figure 3 shows the idealized compensation for

the flow rate to maintain the Reynolds number at a constant level regardless of the temperature changes. In other words, we have to maintain the ratio Q_s/ν at a constant level by scheduling the flow rate accordingly. One of the schemes for scheduling the flow rate is the use of a linear bypass resistor in parallel with the supply nozzle as shown in figure 4. The value of a linear resistor is proportional to the dynamic viscosity so that the flow through the resistor increases as the liquid temperature increases. As a result, for a constant total flow rate, flow through the LPA supply nozzle will decrease.

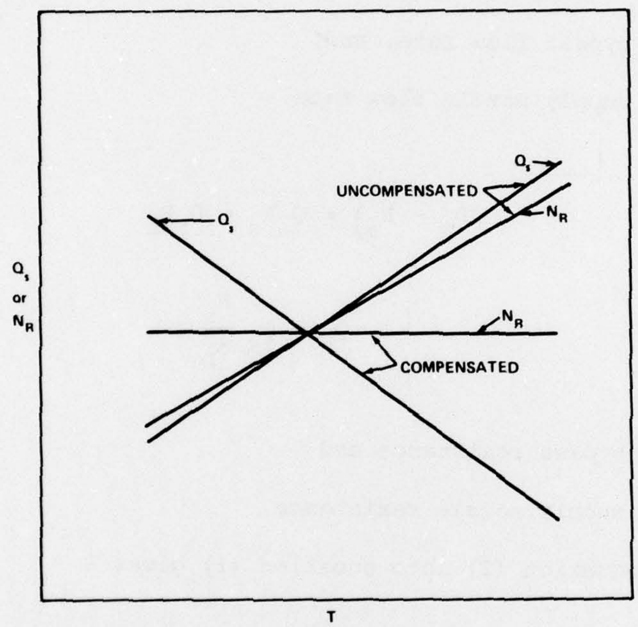

Figure 3. Supply flow rate, Q_s, and Reynolds number, N_R, versus temperature T.

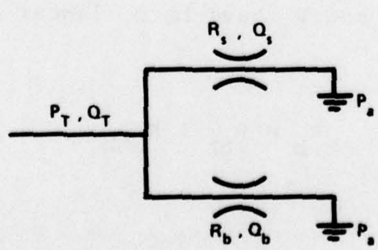

Figure 4. Schematic of supply nozzle with bypass resistor.

3.1 Analysis

From figure 4, we can write

$$Q_T = Q_s + Q_b \ , \tag{1}$$

where

Q_T = total flow rate,

Q_b = bypass flow rate, and

Q_s = supply nozzle flow rate.

Since

$$\left(P_T - P_a\right) = Q_s R_s = Q_b R_b \ ,$$

then

$$Q_b = Q_s \frac{R_s}{R_b} \ , \tag{2}$$

where

R_b = bypass resistance and

R_s = supply nozzle resistance.

Substituting equation (2) into equation (1) gives

$$Q_s = \frac{Q_T}{1 + \frac{R_s}{R_b}} \ . \tag{3}$$

In general R_b and R_s have both linear and nonlinear components such that

$$R_b = R_{b\ell} + K_b Q_b \ , \tag{4}$$

and

$$R_s = R_{s\ell} + K_s Q_s \ , \tag{5}$$

where

$R_{b\ell}$ = linear component of the bypass resistor,

K_b = coefficient of the nonlinear component of the bypass resistor,

$R_{s\ell}$ = linear component of the supply nozzle, and

K_s = coefficient of the nonlinear component of the supply nozzle.

Substituting equations (4) and (5) into equation (3) yields

$$Q_s = \frac{Q_T}{1 + \dfrac{R_{s\ell} + K_s Q_s}{R_{b\ell} + K_b Q_b}} \quad . \tag{6}$$

Equation (6) is the governing equation for the bypass system. In general, $R_{s\ell}$, $R_{b\ell}$, K_b, and K_s are functions of the fluid temperature. For hydraulic fluid within the desired temperature range, K_b and K_s can be assumed to be constant because the density, ρ, remains almost constant. The linear components, $R_{b\ell}$ and $R_{s\ell}$, are, however, dependent on the fluid temperature because of viscosity changes due to temperature variations. The most effective compensation occurs when $R_{s\ell}$ and K_b approach zero so that equation (6) becomes

$$Q_s = \frac{Q_T}{1 + \dfrac{K_s Q_s}{R_{b\ell}}} \quad . \tag{7}$$

Equation (7) describes the upper limit of the linear resistor bypass method.

In terms of Q_s, the Reynolds number is

$$N_R = Q_s / b_s \nu \quad . \tag{8}$$

3.2 Flow Resistance of LPA Supply Nozzle

The supply nozzle of the LPA can be represented by a rectangular channel with variable width as shown in figure 5.

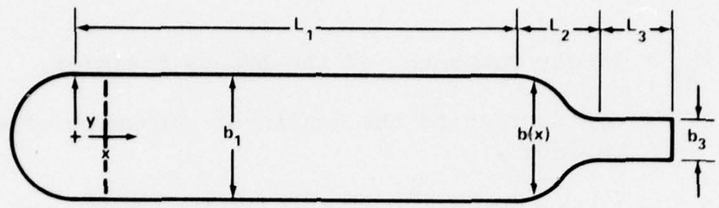

Figure 5. Schematic of supply nozzle of laminar proportional amplifier.

Bellman,[1] using Rouse's velocity profile, derives the resistance for a fully developed flow in a rectangular channel as

$$R = \frac{\mu L}{h^4 \left[\frac{\sigma}{12} + \frac{2}{\pi 5} \sum_{m=1}^{\infty} \frac{(1 - \cos m\pi)^2}{m^5} \frac{\left(-2e^{m\sigma\pi} - 2e^{-m\sigma\pi} + 4\right)}{e^{m\sigma\pi} - e^{-m\sigma\pi}}\right]}, \tag{9}$$

where

b = channel width,

h = channel depth,

L = length of the channel,

μ = dynamic viscosity, and

σ = local aspect ratio $\left(\sigma = \frac{h}{b}\right)$.

It should be noted that the resistance of fully developed channel flow is dependent only on the geometry and the dynamic viscosity of the fluid. Besides the linear component, we have to include the pressure drop due to flow development. Therefore, the total pressure drop, Δp, for a flow through a rectangular channel can be expressed as

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[1]*R. H. Bellman, Fluidic Proportional Amplifier for Very Low Reynolds Numbers, Fluidic State-of-the-Art Symposium, Vol. 1, Harry Diamond Laboratories (1974).*

$$\Delta p = \frac{\mu Q}{h^4} LD + K\rho \frac{Q^2}{A^2} \quad , \tag{10}$$

where

K = flow development coefficient and

$$D = \frac{1}{\frac{\sigma}{12} + \frac{2}{\pi 5} \sum_{m=1}^{\infty} \frac{(1 - \cos m\pi)^2}{m^5} \frac{\left(-2e^{m\sigma\pi} - e^{-m\sigma\pi} + 4\right)}{e^{m\sigma\pi} - e^{-m\sigma\pi}}} \ . \tag{11}$$

In calculating the linear resistance in the converging section of the supply nozzle, we assume that the nozzle can be divided into small rectangular sections, as shown in figure 6, such that the total linear resistance can be calculated as

$$R_{\ell 2} = \sum_{i=1}^{n} \frac{\mu}{h^4} \left(\Delta X_i D_i\right) \ . \tag{12}$$

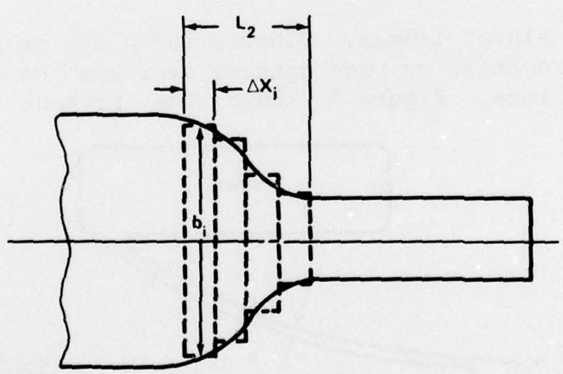

Figure 6. Approximate presentation of the converging section of laminar proportional amplifier supply nozzle.

In the supply nozzle (fig. 5), we also have to include the effect due to the converging section. Therefore, the total pressure drop for the supply nozzle can be written as

$$\Delta p_s = \frac{\mu Q_s}{h^4}\left(L_1D_1 + \sum_{i=1}^{n} X_iD_i + L_3D_3\right) + \frac{K\rho Q_s^2}{(hb_1)^2} + \frac{1}{2}\left(\frac{\rho Q_s^2}{h^2}\right)\left[\left(\frac{1}{b_1^2}\right) - \left(\frac{1}{b_3^2}\right)\right], \quad (13)$$

and the total resistance can be written as

$$R_s = \frac{\Delta p_s}{Q_s} = \frac{\mu}{h^4}\left(L_1D_1 + \sum_{i=1}^{n} \Delta X_iD_i + L_3D_3\right) + \frac{K\rho Q_s}{(hb_1)^2} + \frac{1}{2}\left(\frac{\rho Q_s}{h^2}\right)\left[\left(\frac{1}{b_1^2}\right) - \left(\frac{1}{b_3^2}\right)\right]. \quad (14)$$

It is assumed that the contribution due to developing flow in sections 2 and 3 can be neglected.

3.3 Linear Bypass Resistor Design

From equation (10), if

$$\frac{\mu LD}{h^4} >> \frac{K\rho Q}{A^2}, \quad (15)$$

the resistor is almost linear. Since μ and ρ are properties of the fluid, the only parameters we have control over are the geometric parameters and the flow rate. Figure 7 shows the present design of the

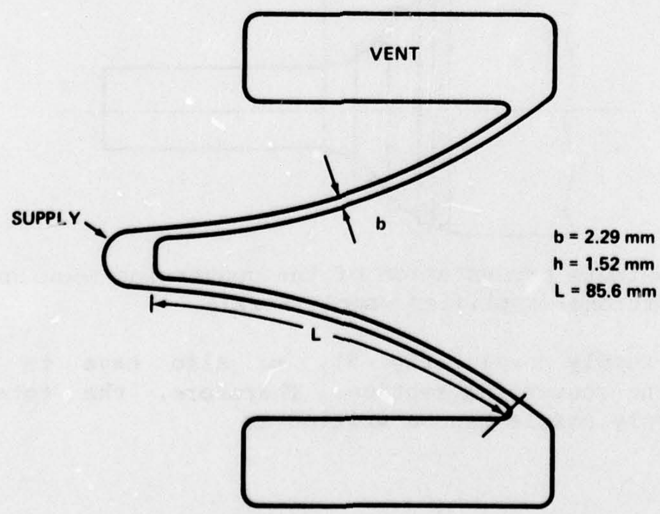

Figure 7. Schematic of bypass resistor.

linear bypass resistor. The design conforms to the LPA configuration so that the bypass resistor can be stacked in parallel with the LPA supply and venting manifolds to vary the resistance incrementally.

As mentioned earlier in section 3, the linear components, R_{sl} and R_{bl}, are dependent on the fluid temperature viscosity. From equation (10), we can write

$$R_s = R_{sl} + K_s Q_s \ , \tag{16}$$

where

$$R_{sl} = R_{l\mu} \ .$$

In order to simplify the calculation, let us normalize the following quantities at the operating point such that

$$R_s = R_l \mu + K_s Q_s = 1 \ , \tag{17}$$

$$\mu = 1 \ , \text{ and} \tag{18}$$

$$Q_s = 1 \ . \tag{19}$$

Substituting equations (18) and (19) into (17) produces

$$R_l + K_s = 1 \text{ or} \tag{20}$$

$$R_l = 1 - K_s \ .$$

From the definition of the discharge coefficient, c_d, as given by Manion and Drzewiecki,[2] one can write

$$c_d = \left(\frac{K_s Q_s}{R_{sl} + K_s Q_s} \right)^{1/2} \ . \tag{21}$$

---

[2] *F. Manion and T. Drzewiecki, Analytical Design of Laminar Proportional Amplifier, Fluidic State-of-the-Art Symposium, Vol. 1, Harry Diamond Laboratories (1974).*

At the operating point, equation (22) becomes

$$c_d = \left(\frac{K_s}{R_1 + K_s}\right)^{\frac{1}{2}} . \tag{22}$$

Substituting equation (20) into (22) and solving for K_s, we have

$$K_s = c_d^2 , \tag{23}$$

and equation (20) becomes

$$R_1 = 1 - c_d^2 . \tag{24}$$

Since the bypass resistor can be designed to have a very small nonlinear component, it is assumed that R_b is linear and can be written as

$$R_b = R_b'\mu , \tag{25}$$

where R_b' is the geometric constant for the bypass resistor. With the above assumptions, equation (6) becomes

$$Q_s = \frac{-\left(R_1 + R_b'\right) + \left(\left[\left(R_1 + R_b'\right)\mu\right]^2 + 4K_s Q_T R_b'\mu\right)^{\frac{1}{2}}}{2K_s} . \tag{26}$$

With the aid of the assumption on normalization, one can show that

$$R_b' = \frac{1}{Q_T - 1} . \tag{27}$$

In terms of μ, c_d, and Q_T, equation (26) becomes

$$Q_s = \frac{-\left(1 - c_d + \frac{1}{Q_T - 1}\right)\mu + \left\{\left[\left(1 - c_d^2 + \frac{1}{Q_T - 1}\right)\mu\right]^2 + 4Q_T c_d^2 \frac{\mu}{Q_T - 1}\right\}^{\frac{1}{2}}}{2c_d^2} . \tag{28}$$

Equation (28) is the desired expression for Q_s as a function of μ, c_d, and Q_T. For an ideal nozzle, $c_d = 1$ and equation (28) becomes

$$Q_s = \frac{\frac{\mu}{1 - Q_T} + \left[\left(\frac{\mu}{Q_T - 1}\right)^2 + 4\mu\left(\frac{Q_T}{Q_T - 1}\right)\right]^{\frac{1}{2}}}{2} . \quad (29)$$

The above equation describes the upper limits of the linear resistor bypass as a function of μ and Q_T.

The effectiveness of the linear resistor bypass can be shown by the ratio between the compensated and uncompensated Reynolds number ranges over the same temperature or viscosity range. This ratio can be written as

$$\eta = \frac{\left(N_{Rf} - N_{Ri}\right)_c}{\left(N_{Rf} - N_{Ri}\right)_u} , \quad (30)$$

where N_{Ri} and N_{Rf} are the initial and final Reynolds numbers, respectively, and the subscripts c and u correspond to compensated and uncompensated. Since $\left(N_{Ri}\right)_c = \left(N_{Ri}\right)_u$, equation (30) can be written as

$$\eta = \frac{\left(\frac{N_{Rf}}{N_{Ri}} - 1\right)_c}{\left(\frac{N_{Rf}}{N_{Ri}} - 1\right)_u} . \quad (31)$$

Equation (31) is the desired expression for the effectiveness of the linear resistor bypass.

4. EXPERIMENTAL TEST SETUP AND TEST RESULTS

4.1 Experimental Test Setup

In this study, a comprehensive experimental program was conducted to evaluate the flow shunting effectiveness of the linear resistor bypass. Figure 8 shows the schematic of the test setup. Dow Corning Silicone 200 fluid was chosen as the working fluid because its viscosity and density are very stable, and it is easier to handle than 5606 hydraulic oil. In this test the fluid temperature can be controlled between 15 and 55 C with an error of ±0.25 C. All the

pressure measurements were made with Barocell pressure transducers, and the flow rates were measured with calibrated orifice flowmeters. In order to reduce the pump noise, an accumulator and an inline screen filter were placed model between the pump and the test section. The LPA tested was an HDL (3.1.1008C) with a 2.5-mm width supply nozzle.

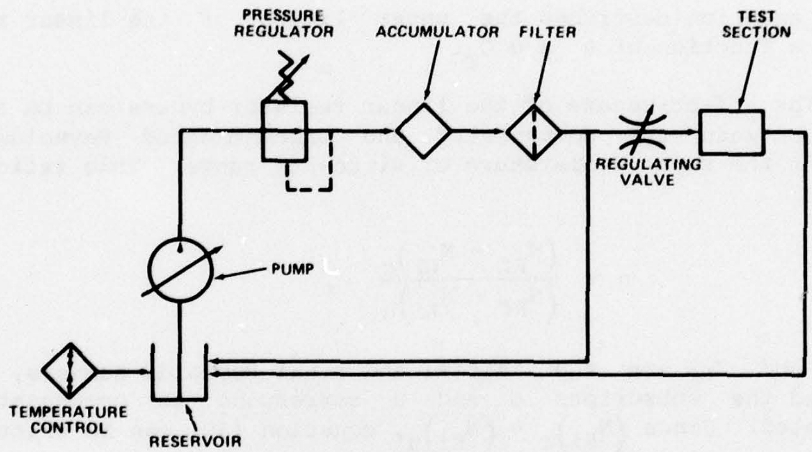

Figure 8. Schematic of test setup.

4.2 Test Results and Theoretical Calculations

In this test program, the pressure-flow (P-Q) characteristics of both the LPA supply nozzle and the resistor were measured at fluid temperatures of 15, 25, 35, 45, and 55 C. Figure 9 shows the experimental P-Q characteristics of the LPA as compared with the theoretical calculation using equation (14) for aspect ratios of 1.25, 2.5, and 5. The agreement is good. Similarly, figure 10 shows the P-Q characteristics for two, four, and eight linear resistors in parallel. Again the test results and the theoretical predictions are in good agreement. It should be noted that the value of the pressure drops has been multiplied by a constant, K1, to account for the pressure drop in the supply manifold. It should also be noted that both the test results and theoretical predictions indicate that the present resistor is "linear" within the test range.

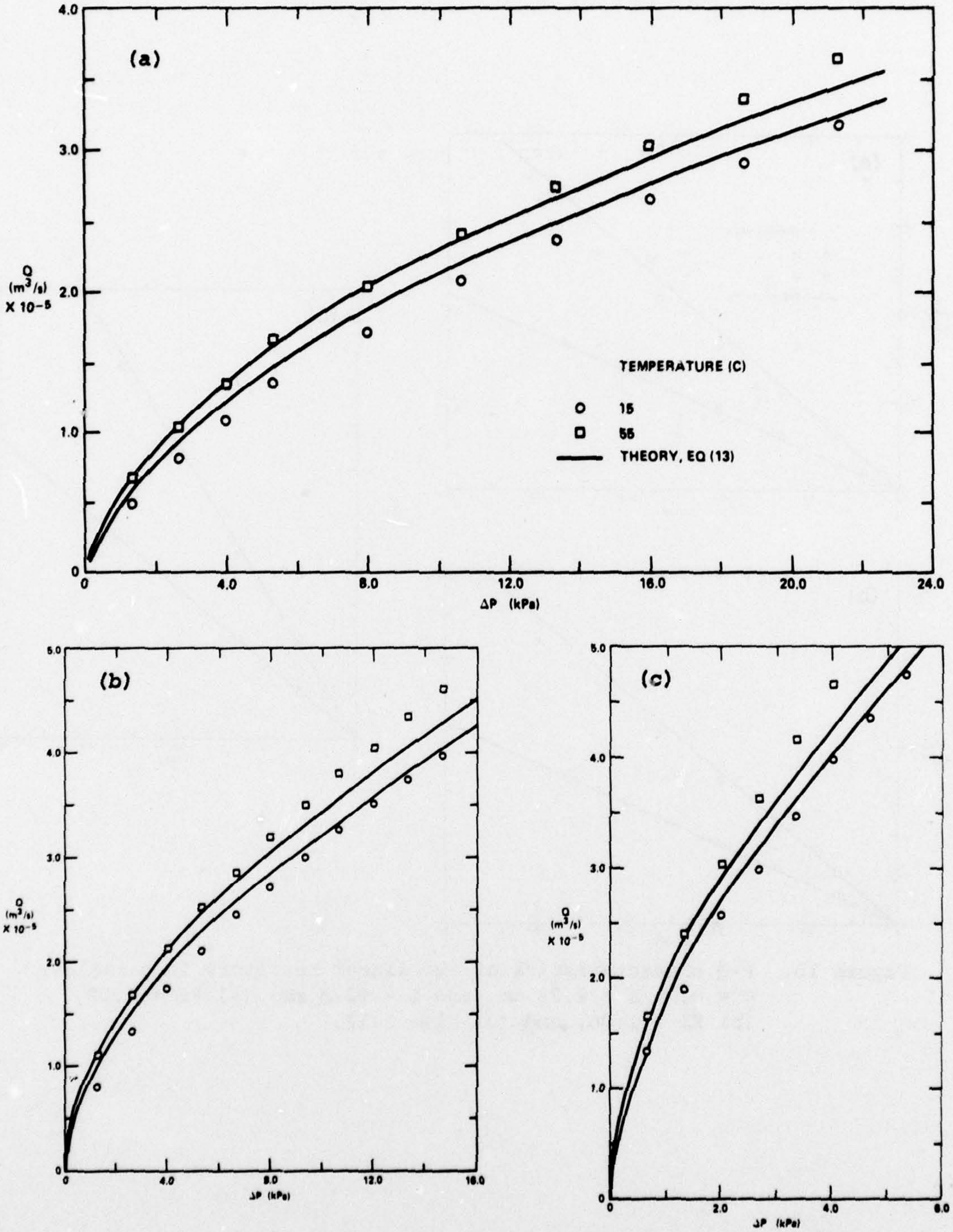

Figure 9. P-Q characteristics of laminar proportional amplifier supply nozzle; K = 0.6, and b_s = 2.5 mm; (a) σ = 1.25, (b) σ = 5, and (c) σ = 2.5.

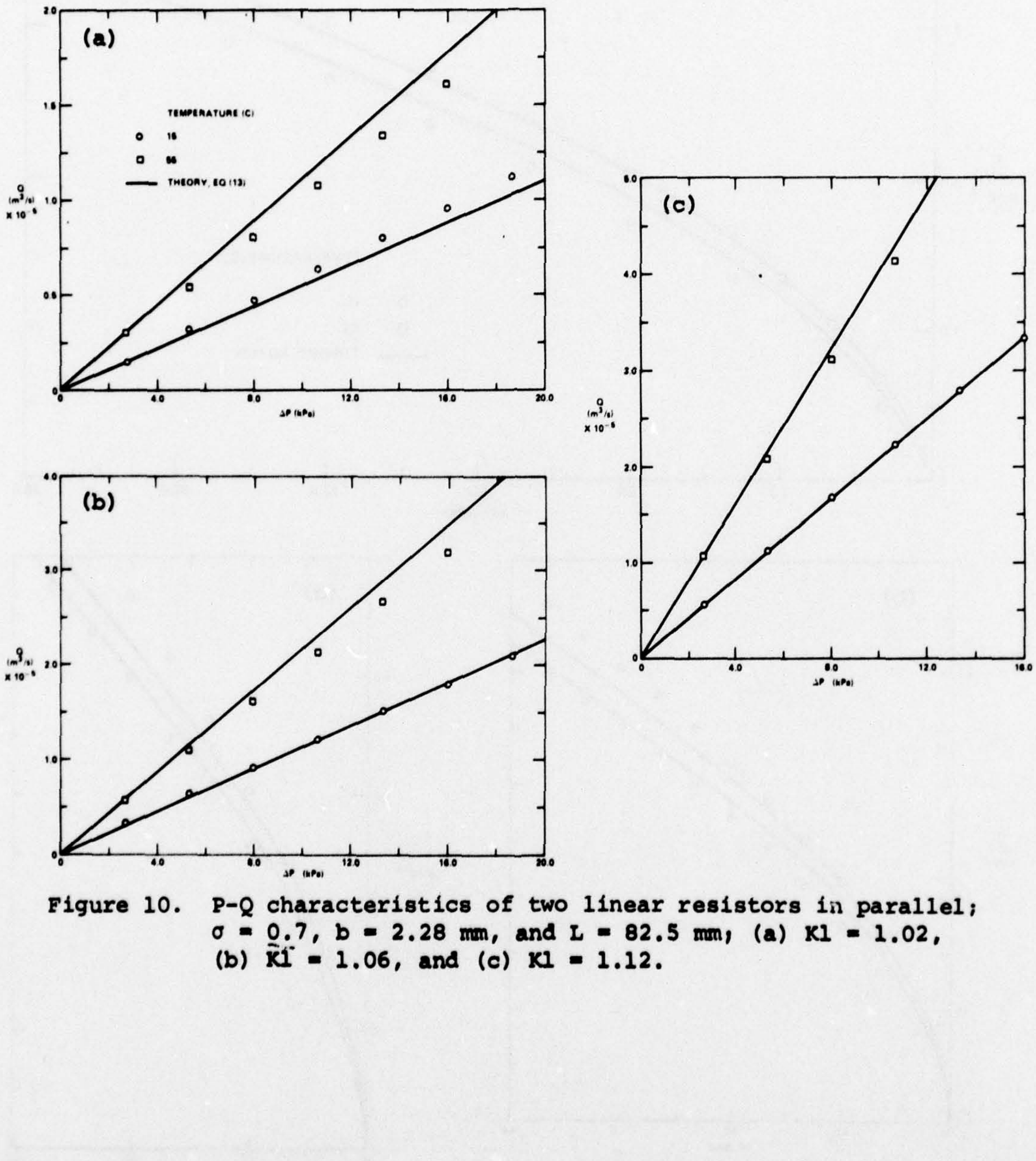

Figure 10. P-Q characteristics of two linear resistors in parallel; $\sigma = 0.7$, $b = 2.28$ mm, and $L = 82.5$ mm; (a) $Kl = 1.02$, (b) $Kl = 1.06$, and (c) $Kl = 1.12$.

One of the most important performance characteristics of the LPA is the pressure gain. Figure 11 shows the blocked-load pressure gain, G_p, of the LPA versus the Reynolds number, $N_R = \overline{U}h/\nu$. In general, G_p increases as N_R increases. In order to evaluate the effectiveness of the linear resistor bypass on the pressure gain, the pressure gain was measured at various constant flow rates over the temperature range of 15 to 55 C. Figure 12 shows the normalized pressure gain versus temperature at various constant flow rates set at 25 C. Once again we see that G_p increases as the fluid temperature increases because the Reynolds number increases as the temperature increases for a constant flow rate. Figure 13 shows the normalized pressure gain versus temperature for various constant total flow rates for different combinations of the LPA and linear resistors.

In order to illustrate the effectiveness of linear resistor bypass, the uncompensated pressure gain characteristics are compared with several compensated gain characteristics in figure 14. Another way to measure the effectiveness of the linear resistor bypass is to compare the Reynolds number changes for the uncompensated, ideal compensated (eq (7)), and compensated (eq (6)) LPA over the same temperature range as shown in figure 15 for various combinations of LPA aspect ratios and bypass resistors. As indicated in these figures, for a given initial LPA supply nozzle Reynolds number, the ratio of the supply nozzle flow, Q_s, to the total flow, Q_T, determines the amount of compensation for the Reynolds number. An increase of the ratio Q_s/Q_T decreases the amount of compensation, while a decrease of Q_s/Q_T tends to increase the effectiveness of the compensation as shown in figures 15(g) and 15(c), respectively.

Figure 16 shows the predicted Reynolds number changes as compared with the experimental results. Figure 17 shows the theoretical limits of the Reynolds number ratio as a function of the Q_s/Q_T ratio for an ideal linear resistor bypass (K_{bl}, $R_{sl} = 0$) for $\mu_f = 1/2\ \mu_i$ and $\mu_f = 1/5\ \mu_i$. These limits were calculated by using equations (7) and (8) for various constant values of Q_T. Figure 18 shows the variations of η versus μ_f/μ_i for various values of Q_T and c_d.

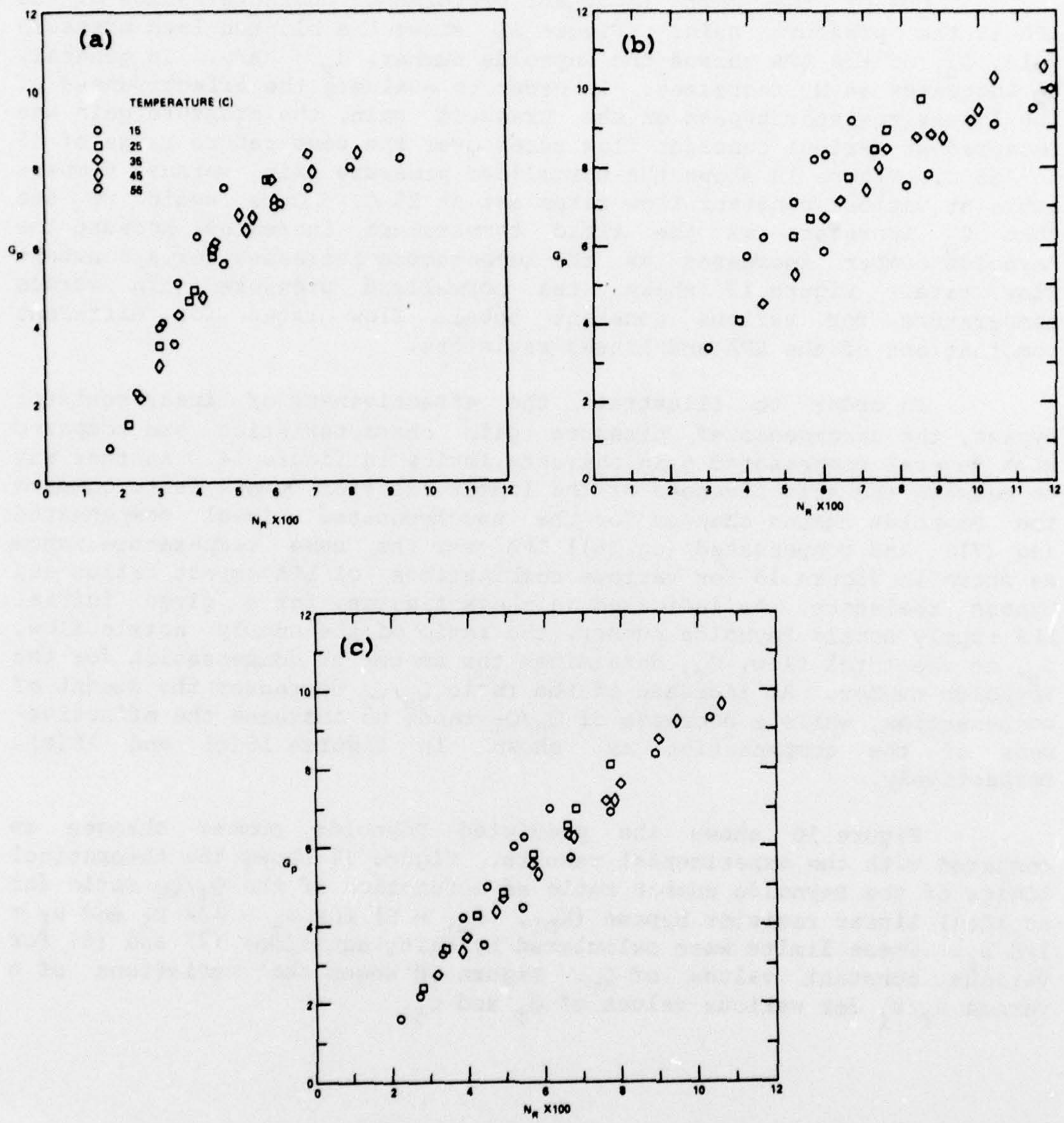

Figure 11. Pressure gain, G_p, versus Reynolds number, N_R; (a) $\sigma = 1.25$, (b) $\sigma = 2.50$, and (c) $\sigma = 5.0$.

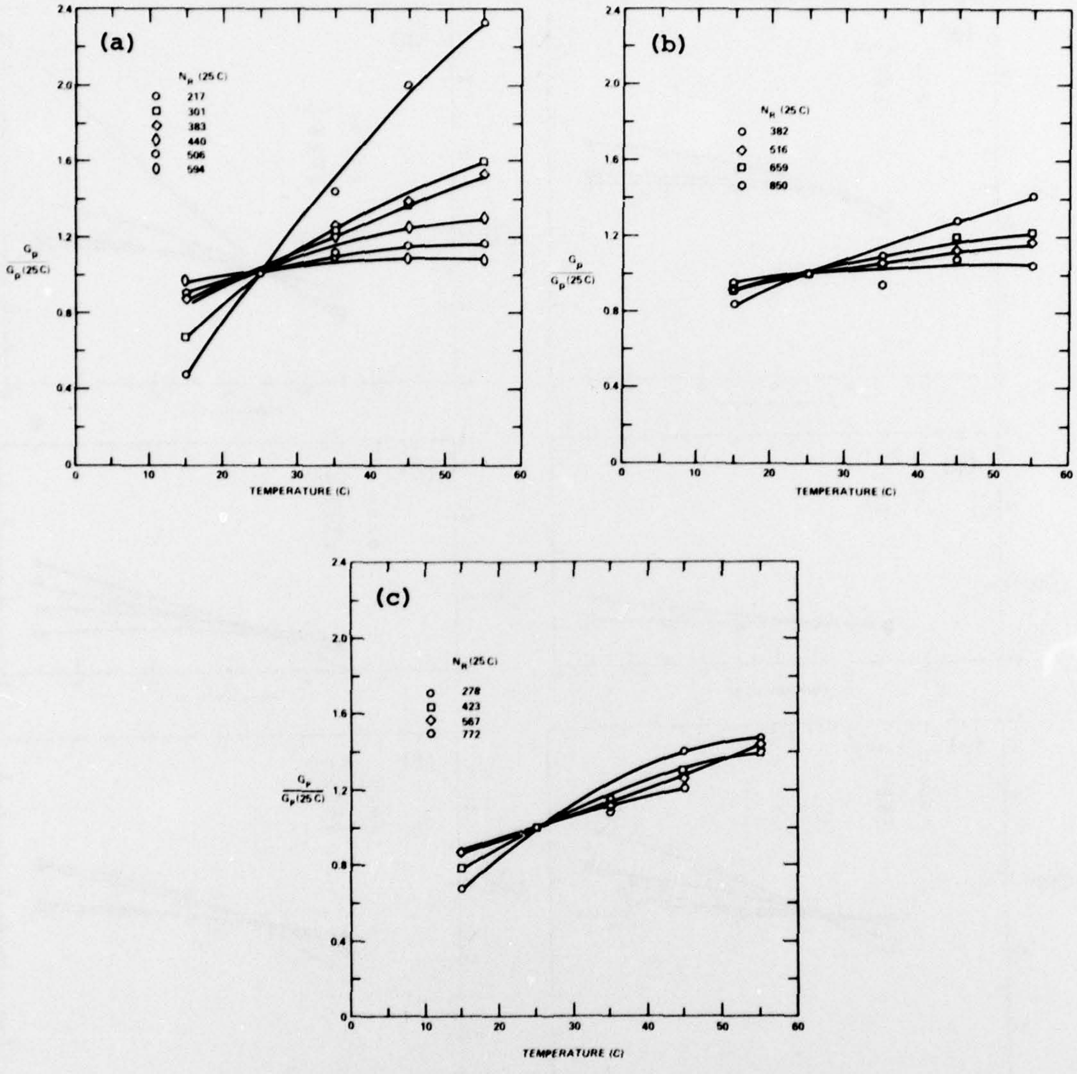

Figure 12. Normalized pressure gain versus temperature at various constant flow rates; (a) σ = 1.25, (b) σ = 2.5, and (c) σ = 5.0.

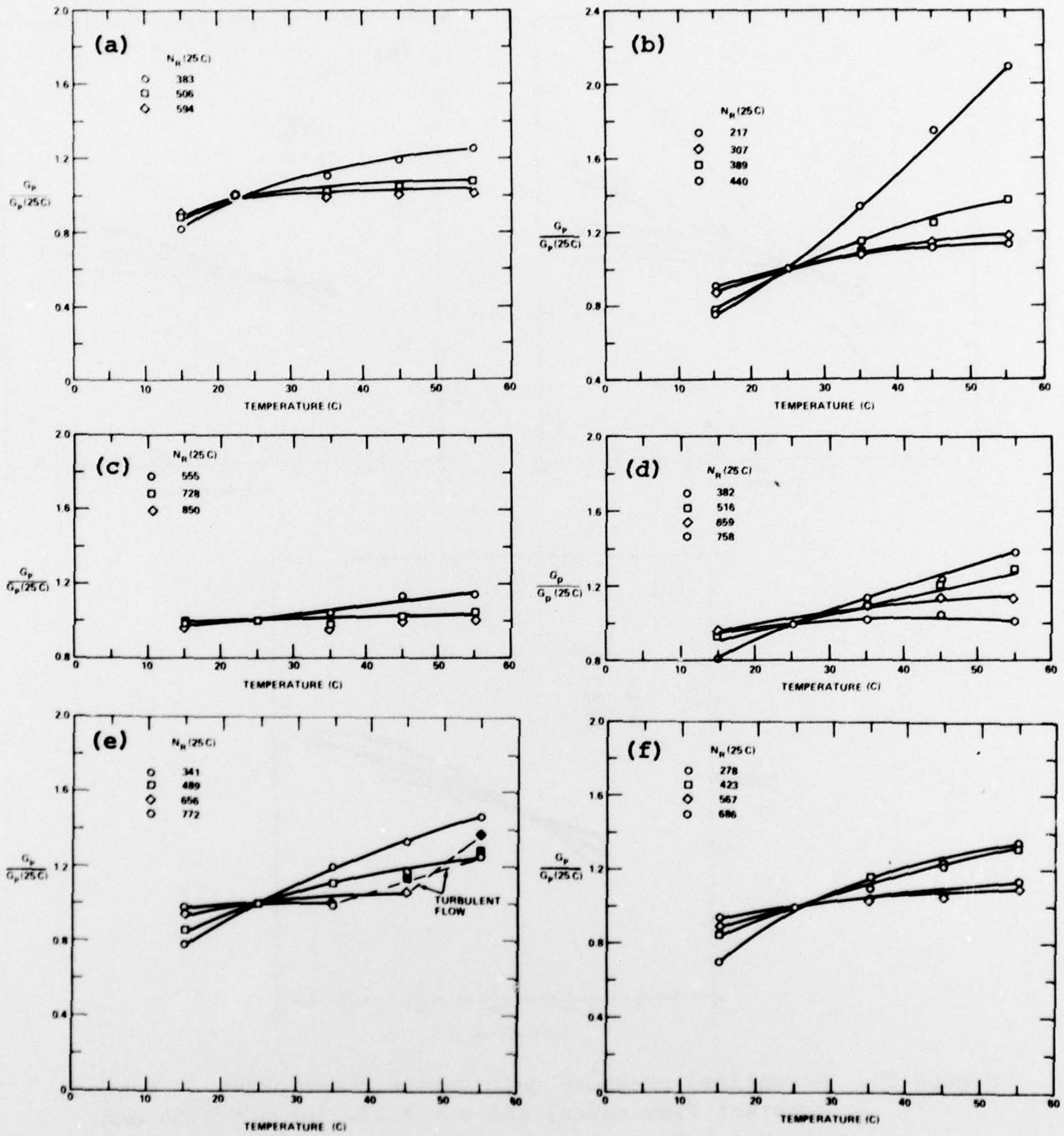

Figure 13. Normalized pressure gain versus temperature at various constant total flow rates; (a) σ = 1.25 and four resistors in parallel, (b) σ = 1.25 and eight resistors in parallel, (c) σ = 2.5 and four resistors in parallel, (d) σ = 2.5 and eight resistors in parallel, (e) σ = 5.0 and four resistors in parallel, and (f) σ = 5.0 and eight resistors in parallel.

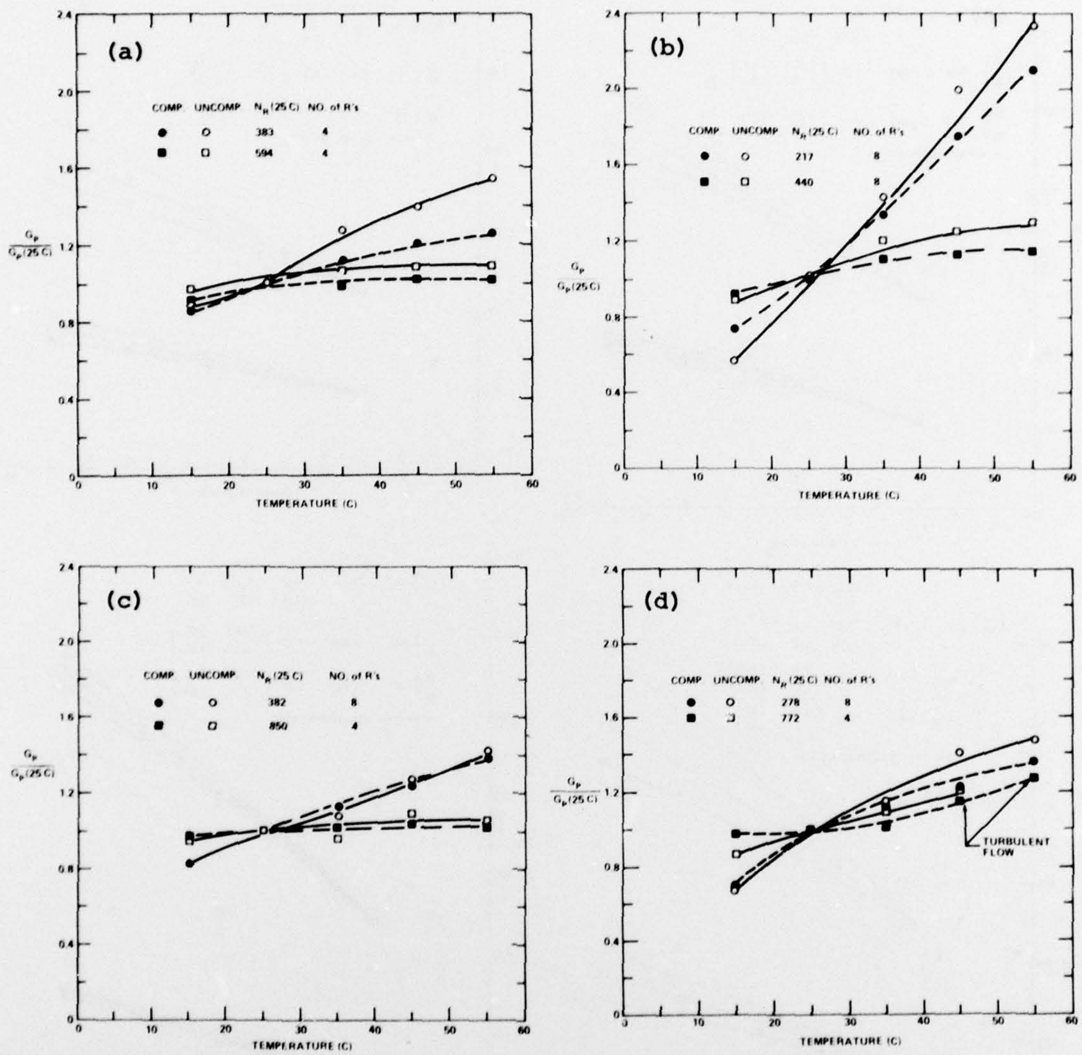

Figure 14. Comparison between the uncompensated and the compensated pressure gain versus temperature; (a) $\sigma = 1.25$ and four resistors in parallel, (b) $\sigma = 1.25$ and eight resistors in parallel, (c) $\sigma = 2.5$, and (d) $\sigma = 5.0$.

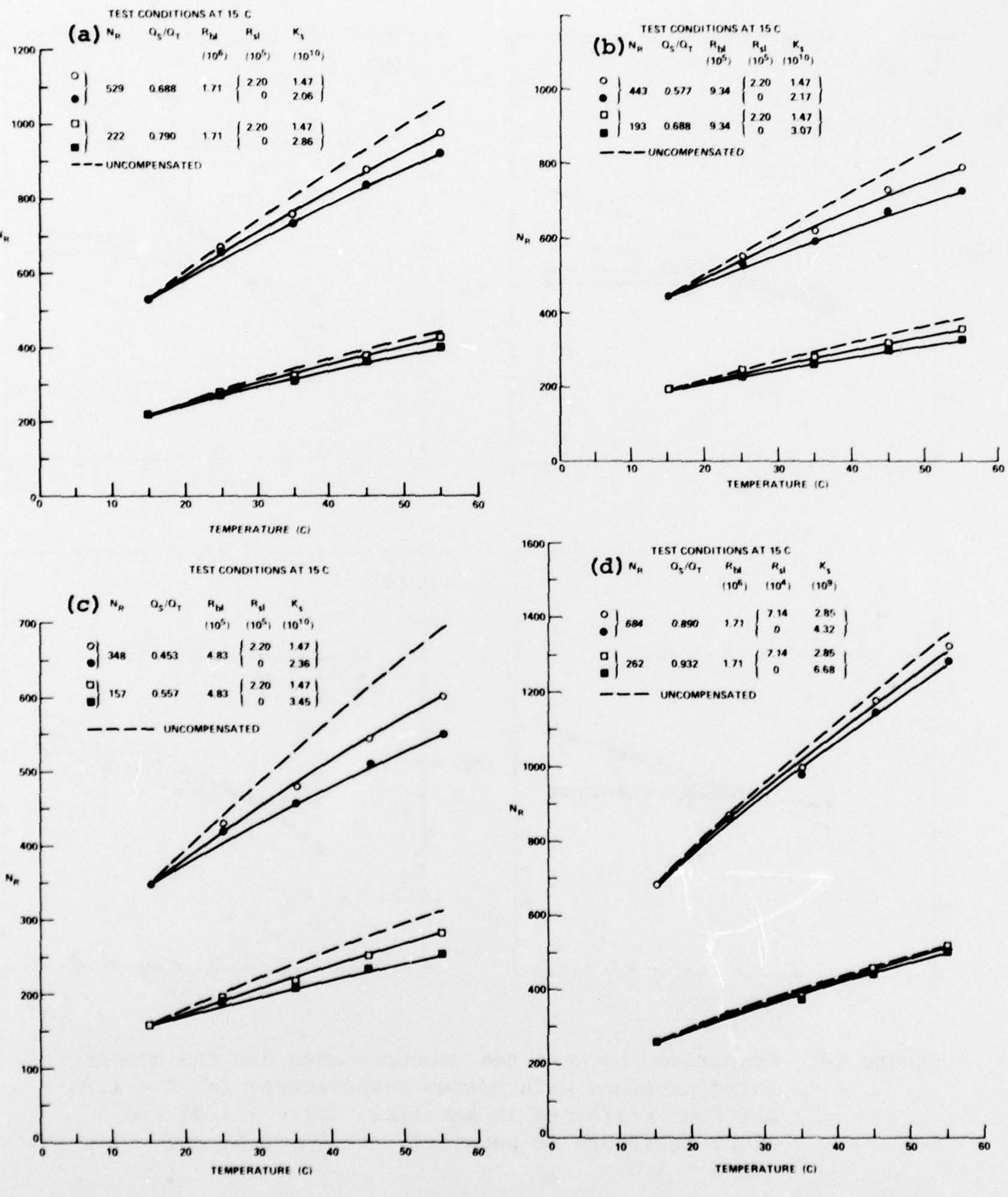

Figure 15. Variation of the laminar proportional amplifier supply nozzle Reynolds number, N_R, versus temperature for various compensations; (a) σ = 1.25, two resistors in parallel, (b) σ = 1.25, four resistors in parallel, (c) σ = 1.25, eight resistors in parallel, and (d) σ = 2.50, two resistors in parallel.

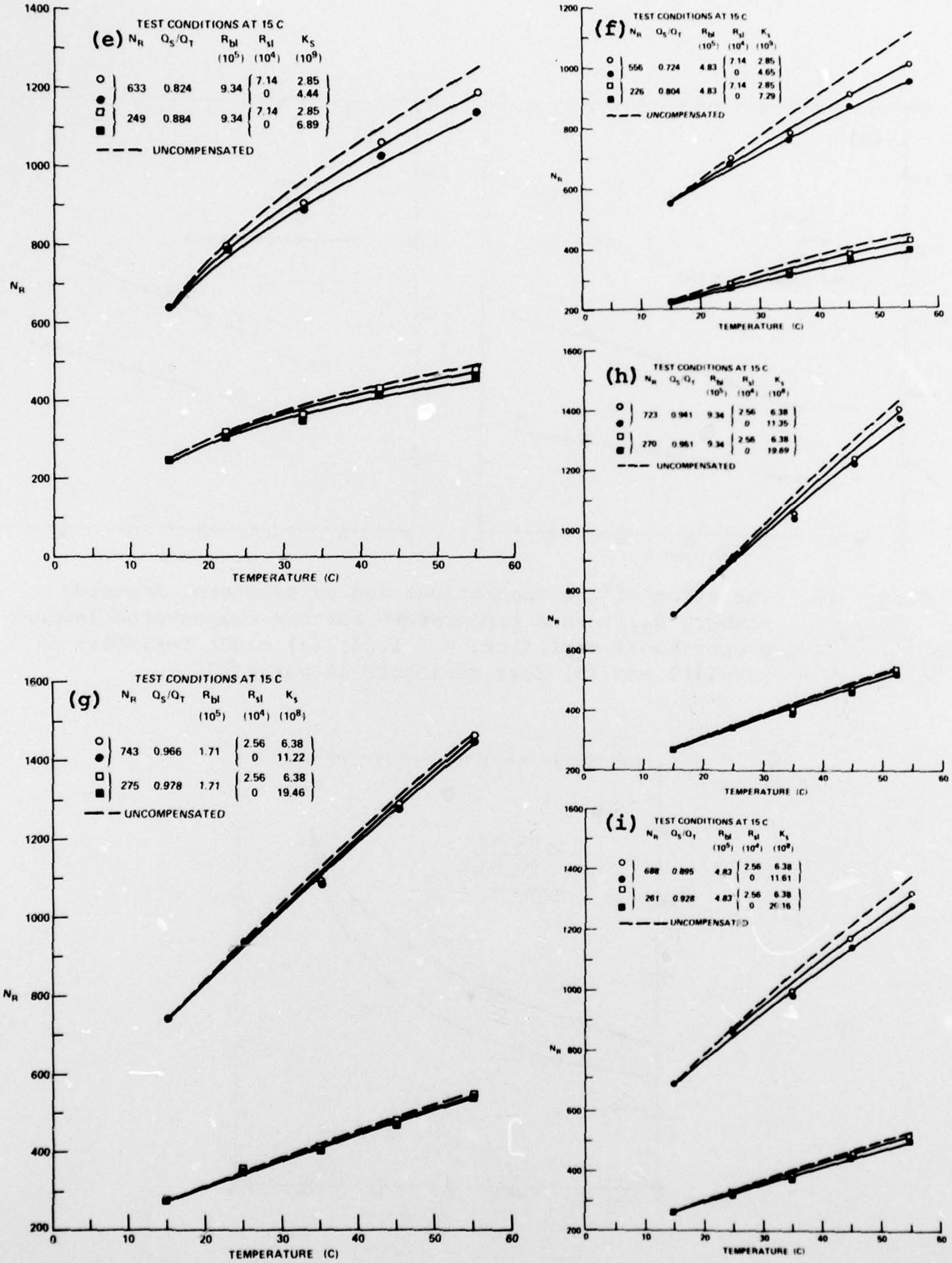

Figure 15. (e) σ = 2.50, four resistors in parallel, (f) σ = 2.50, eight resistors in parallel, (g) σ = 5.0, two resistors in parallel, (h) σ = 5.0, four resistors in parallel, and (i) σ = 5.0, eight resistors in parallel.

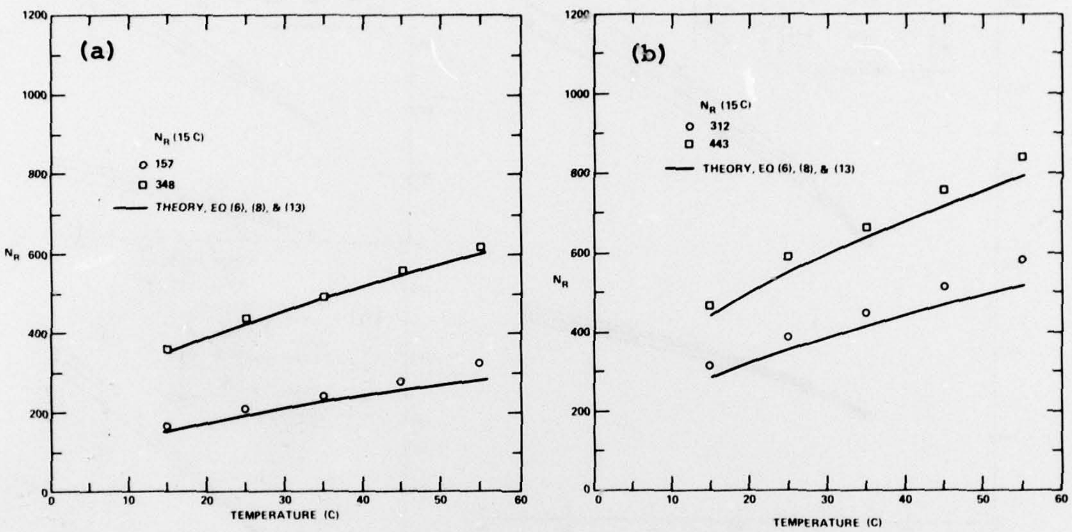

Figure 16. Variation of the theoretical and experimental Reynolds number, N_R, versus temperature for the compensated laminar proportional amplifier, $\sigma = 1.25$; (a) eight resistors in parallel and (b) four resistors in parallel.

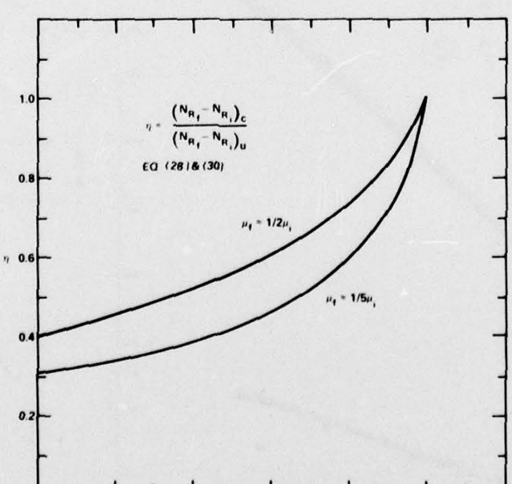

Figure 17. Ideal Reynolds number ratio; η versus Q_S/Q_T for the ideal linear resistor bypass with $\mu_f = 1/2\ \mu_i$ and $\mu_f = 1/5\ \mu_i$.

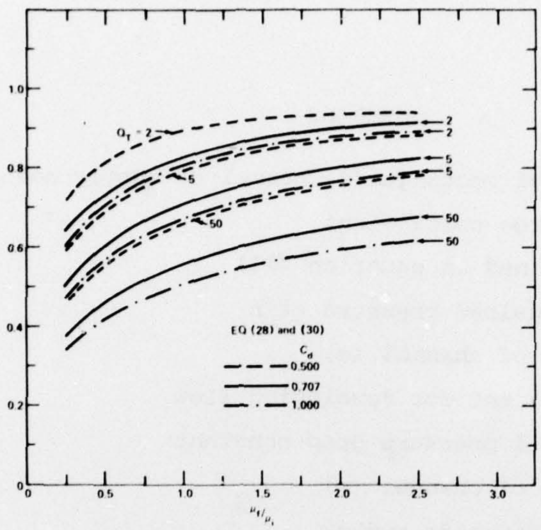

Figure 18. Variation of η versus μ_f/μ_i for various values of Q_T and c_d.

5. SUMMARY AND RECOMMENDATION

A comprehensive experimental and theoretical study of the linear resistor bypass for the LPA supply has been conducted. In general the theoretical and the experimental results are in good agreement. The results of this study indicate that the use of a linear resistor bypass for temperature compensation in the present LPA design yields a limited success. The method is limited because the supply nozzle of the LPA has a large linear component as indicated both by the equations obtained by the least-squares fit of the data and the theoretical calculations. Even if we can design the LPA supply nozzle with a pure orifice, the effectiveness of the linear resistor bypass is still limited, as indicated by figure 17, which shows the upper limits of the linear resistor bypass as given by equation (7).

Both the theoretical and experimental results indicate that the effectiveness of the linear resistor bypass method is dependent on the ratio Q_s/Q_T and the linear resistance component of the LPA supply nozzle. This is illustrated clearly by the results shown in figures 15(c) and (g) for small and large values of Q_s/Q_T, respectively. Over the temperature range of 15 to 55 C, the Reynolds number change has been reduced by 30 percent for Q_s/Q_T equal to 0.453 while there is only a 2-percent reduction for Q_s/Q_T equal to 0.966. The above results also show that it is necessary to more than double the total flow in order to have a 30-percent reduction of the Reynolds number range for the temperature range of 15 to 55 C. Therefore a compromise is required between the amount of compensation and the total supply flow to the system.

In order to compensate the Reynolds number of the LPA over the military temperature range, other, more effective methods of temperature compensation should be investigated.

SYMBOLS

b	width of rectangular channel or supply nozzle (m)
c_d	discharge coefficient
D	as defined in equation (11)
G_p	blocked-load pressure gain
h	height of channel (m)
K	coefficient for developing flow
$K1$	manifold pressure drop constant
L	length of channel (m)
N_R	$\bar{U}h/\nu$, Reynolds number
p	pressure (kN/m^2)
Q	flow rate (m^3/s)
R	resistance (kg/m^4-s)
T	temperature (C)
$\bar{U}$	average velocity (m/s)
x	length of channel or distance (m)
η	$(N_{Rf} - N_{Ri})_c (N_{Rf} - N_{Ri})_u$
μ	dynamic viscosity (kg/m-s)
ρ	density (kg/m^3)
σ	aspect ratio (h/b)
ν	kinematic viscosity (m^2/s)

Subscripts

1,2,...i	index	m	index
a	ambient	n	index
b	bypass	s	supply
c	compensated	sp	splitter
i	index, initial	T	total
f	final	u	uncompensated
ℓ	linear		

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